THESIS FOR THE DEGREE OF LICENTIATE OF ENGINEERING

MODELLING THE INTEGRATION OF ADDITIVE MANUFACTURING TECHNOLOGIES IN DESIGN OF SPACE COMPONENTS

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Modelling the integration of Additive Manufacturing technologies in design for space components

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Cover: Satellite antenna (Article C) modularized according to multidisciplinary design requirements.

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ABSTRACT

Products for space applications are traditionally costly and produced in small batches. Moreover, they must be able to withstand extreme environments and meet tough requirements when in operation, as the ability to maintain and repair them is limited. However, nowadays cost and lead time reduction are becoming important driving forces for space manufacturers. New technologies such as Additive manufacturing (AM) are attractive for space companies as they enable new product functionalities or lower production costs, fostering company capabilities and permanence in the market. However, the lack of knowledge and experience in AM hinders its implementation in highly regulated industries such as the space industry.

In this thesis, a first approach of a model-based Design for Additive Manufacturing (DfAM) design support is presented to facilitate the introduction of AM in components for space applications. The design support aims at redesigning components for AM, taking advantage of AM design freedom but considering AM limitations as well. Moreover, to address the needs of the space industry, relevant design trade-offs of space products, such as weight/cost reduction, component modularity or adaptability to market changes are included in the DfAM design support. The applicability of the design support has been demonstrated in the design of different space products (such as satellite antennas) and in the context of three different Swedish manufacturers of space components. A first validation of the design support and the redesigned space components was performed with industrial practitioners.

The proposed design support was developed for the introduction of a new manufacturing technology in space components. As technologies for space applications advance at a fast pace, future research needs to be performed to adapt the design support to enable the introduction of technologies that are not manufacturing related. Moreover, as product development is often concerned with the introduction of multiple technologies in the same product/product family, the impact of technology interactions in product design is of interest and will be studied further.

Keywords: Technology integration, model-based, Additive Manufacturing, space components, DfAM.

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APPENDED PUBLICATIONS

Article A

Borgue O, Panarotto M, Isaksson O (2018) Impact on design when introducing additive manufacturing in space applications. In: Proceedings of the DESIGN 2018 15th International Design Conference, Dubrovnik, Croatia, pp. 997-1008. https://doi.org/10.21278/idc.2018.0412.

Workload distribution: Borgue acted as main author, and performed the literature studies and analyzed its results, which enabled the results and conclusions presented in this article. Moreover, Borgue actively participated on the empirical studies, their documentation and performed most of the writing activities.

Article B

Borgue O, Müller JR, Panarotto M, Isaksson O (2019) Constraints replacement-based design for Additive Manufacturing of satellite components. Function modelling and constraints replacement for additive manufacturing in satellite component design. In: Proceedings of NordDesign 2018.

Workload distribution: Borgue participated on the development of the methodology and article writing. Moreover, has participated on the empirical studies and the development of the models and their validation, and is responsible for the design of the satellite component.

Article C

Borgue O, Panarotto M, Isaksson O (2019) Modular product design for additive manufacturing of satellite components: Maximizing product value with optimization algorithms. Accepted for publication in Journal of concurrent engineering: research and applications.

Workload distribution: Borgue developed the modularization methodology and carried out the empirical studies, validation activities and article writing activities.

Article D

Dordlofva C, **Borgue O**, Panarotto M, Isaksson O (2019) Drivers and Guidelines in Design for Qualification using Additive Manufacturing in Space Applications. In: International conference of engineering design (ICED) 2019.

Workload distribution: Borgue participated on the development of the interviews, their realization and analysis, as well as elaborating the presented results and conclusions. Moreover, participated in the writing process.

ADDITIONAL PUBLICATIONS

The following publications are related to the research presented in this thesis, but do not fully contribute to the findings.

Isaksson O., Eckert C., Borgue O., Hallstedt S.I., Hein A.M., Gericke K., Panarotto M., Reich Y. and Rönnbäck, A.B.Ö. (2019) Perspectives on innovation: The role of engineering design. In Proceedings of the Design Society: International Conference on Engineering Design (Vol. 1, No. 1, pp. 1235-1244). Cambridge University Press.

CONTENTS

LIST OF ACRONYMS

AM	-	Additive Manufacturing
AR	-	Action Research
C	-	Constraint
CC	-	Configurable Component
Cf	-	Functional Constraint
Cm	-	Manufacturing Constraint
CAD	-	Computer Aided Design
CHEOPS	-	Consortium for Hall Effect Orbital Propulsion System
DfAM	-	Design for Additive Manufacturing
DRM	-	Design Research Methodology
DS	-	Design Solution
DSM	-	Design Structure Matrix
EF-M	-	Enhanced Functions-Means
ESA	-	European Space Agency
FBS	-	Function-Behavior-State
FR	-	Functional Requirements
IDAG	-	Infrastructure for Digitalization enabling industrialization of Additive manufacturinG
LPFB	-	Laser Powder-Bed Fusion
NASA	-	National Aeronautics and Space Administration
NFR	-	Non-functional requirements
PD	-	Product Development
RIQAM	-	Radical Innovation and Qualification for Additive Manufacturing
RQ	-	Research Question
W#	-	Workshop number #

1

INTRODUCTION

A short explanation of the research topic and context

Products for space applications are traditionally costly and produced in small batches. They must be able to withstand extreme environments and meet tough requirements when in operation, as the ability to maintain and repair them is limited (Hobday,1998). Components for space applications are often designed for minimum weight while being able to withstand the dynamic conditions of launching and environmental requirements regarding radiation and thermal gradients (Öhrwall Rönnbäck, and Isaksson (2018).

These conditions have shaped the space industry to be risk averse with low production volumes and long development times, where the main actors were governmental and defense agencies such as NASA, ESA or Roscosmos (Hiriart and Saleh, 2010). The launch vehicle Ariane 5, for instance, had its first series of test flights in 1996 and was in development until 2014. Launches with Ariane 5 rockets were performed from 1997 and are still performed nowadays with a frequency of 7 launches per year (ESA, 2019). Their developing and launch cost per unit is estimated in 150 to 170 million euros (Selding, 2015).

However, as the industry evolves (Whitney; 2000), multiple international groups started to compete for commercial markets, fostering the creation of private companies and start-ups in the space sector. Those newly created companies, known as "New Space" companies, are primarily funded by private capital and have a clear objective of increasing production numbers and lowering costs, challenging the traditional ways of space exploration, considered too expensive, time-consuming, and conservative (Prasad, 2017; Martin 2014). The NewSpace company SpaceX, for instance, plans to launch into orbit a satellite constellation with more than 4000 low-cost satellites, 800 of which are expected to be operative by 2020 (Fernholz, 2019).

It is estimated that in the next 10 years, around 10,000 new space enterprises are expected to be started (Henry, 2016). This change in mentality lead to cost and lead time reduction becoming important driving forces for space manufacturers. The launch vehicles Ariane 6, planned to be operational in 2020, were developed expecting major cost reduction from its predecessor Ariane 5 to compete against the low cost of SpaceX launchers (Shalal, 2019).

Due to the increased market competition, disruptive technologies such as *Additive manufacturing* (AM) are attractive for space companies to target new product functionalities or lower production costs, ensuring company permanence in the market and fostering company capabilities. The implementation of additive manufacturing promises increased component

performance due to an increased design freedom and reduced manufacturing costs enabled by weight reduction achieved through efficient material allocation (O´Brien, 2018).
However, when introducing new technologies or manufacturing methods the design process rarely starts from scratch. Design knowledge reuse supports ensuring product reliability and reduce nonessential work shortening the development cycle (Pahl et al., 2007). From its first implementation in 1996, the Ariane 5 has been continuously modified and improved to meet the demands of the commercial market. Although they all preserve the same general architecture, technical design changes are motivated by lessons learned from previous launches (CNES, 2018).
Sometimes, however, when designing for AM (and new technologies in general), some carried-over knowledge and practices related with traditional manufacturing processes can hinder the design process for AM. In the case of AM, traditional manufacturing constrains (such as avoiding designs with internal canals or intricate geometries when casting) are perhaps no longer valid for AM, and at the same time, this new technology encompasses a new set of manufacturing constraints.
Over the last 30 years, AM has been the focus of large development and research projects, but the knowledge and experience about AM are still not well developed and are low compared to traditional manufacturing processes (O'Brien, 2018). Authors such as Lindwall et al. (2017) or O´Brien (2018) agree that the main challenge when implementing metal AM is the lack of experience and the large amount of uncertainties and unknowns around the manufacturing process which affects product design and development, especially in highly regulated industries such as the space industry (Gausemeie, et al., 2013). At the current stage of AM maturity, Design for Additive Manufacturing (DfAM) methodologies for space applications should acknowledge the lack of knowledge about how the physical phenomena and AM processes influence product design and product quality (O'Brien, 2018; Taylor, Manzo and Flansburg, 2016). Moreover, a new design mind set is required to remove unnecessary carried over knowledge about traditional manufacturing technologies and replace it with AM specific knowledge.
Additive Manufacturing technologies are attractive for space companies to target new product functionalities or lower production costs. However, the lack of knowledge and experience in AM hinders its implementation in highly regulated industries such as the space industry. Hence, the objective of this thesis is to develop a better support for AM design based on the implementation of model-based design methodologies purposely adapted for the space industry.

1.1. Research positioning, scope and limitations

The presented work has been carried out at the Systems Engineering Design research group, part of the division of Product Development at the Department of Industrial and Materials Science at Chalmers University of Technology. The research group aims to understand an address the problems and needs faced by product developing (PD) organizations.
In this context, the research presented in this thesis is concerned with the design of complex space products for metal laser powder-bed fusion (LPFB) AM implementing a model-based methodology. The denomination "Space product/component" refers in this thesis to mechanical components for on-orbit space applications, such as the mechanical design of an AM satellite antenna. The characterization of 'complex' refers mainly to the high number of customized components and the amount of knowledge and skills required in production.
This research is based in a context where AM technologies are aligned with company objectives and that one concrete AM technology has already been selected for implementation.

The thesis is not concerned with the selection of the most appropriate AM technology for a certain application, but with the development of an AM design support adapted to the space industry.

This thesis is positioned in the PD activities related to the design of product architectures and product design concepts. Design strategies applied in early phases of the product development process provide tools for dealing with early changes in requirements and design assumptions. Moreover, as knowledge and experience regarding design for AM is limited, its early modelling can facilitate its efficient management and implementation. This early stages in the product development process are identified by Ulrich and Eppinger (2011) as the System-Level Design phase (Figure 1.1.) where the product architecture is generated, product subsystems and interfaces are defined, and preliminary components designs are established. This thesis is not concern with detailed design.

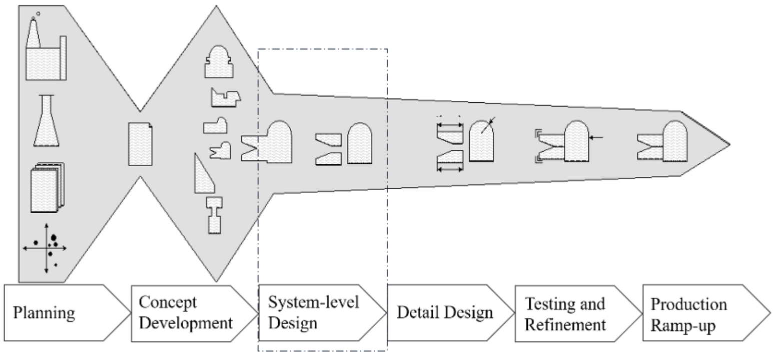


Figure 1.1. Thesis positioned according the PD process proposed by Ulrich and Eppinger (2011).

The thesis can be also positioned in terms of the Vee model (Buede and Miller 2016). In this model, testing activities are developed in parallel with a corresponding phase of the product development process (Figure 1.2). This thesis addresses the product development stages 2 and 3 from Figure 1.2, namely “Develop System Performance Specification and System Validation Plan” and “Expand Performance Specification into CI (configuration items) “Design-to” specifications and CI verification plan”. The point to be made is that the main focus is seton early phases, not on the phases where there is a clear, embodied concept readily available.

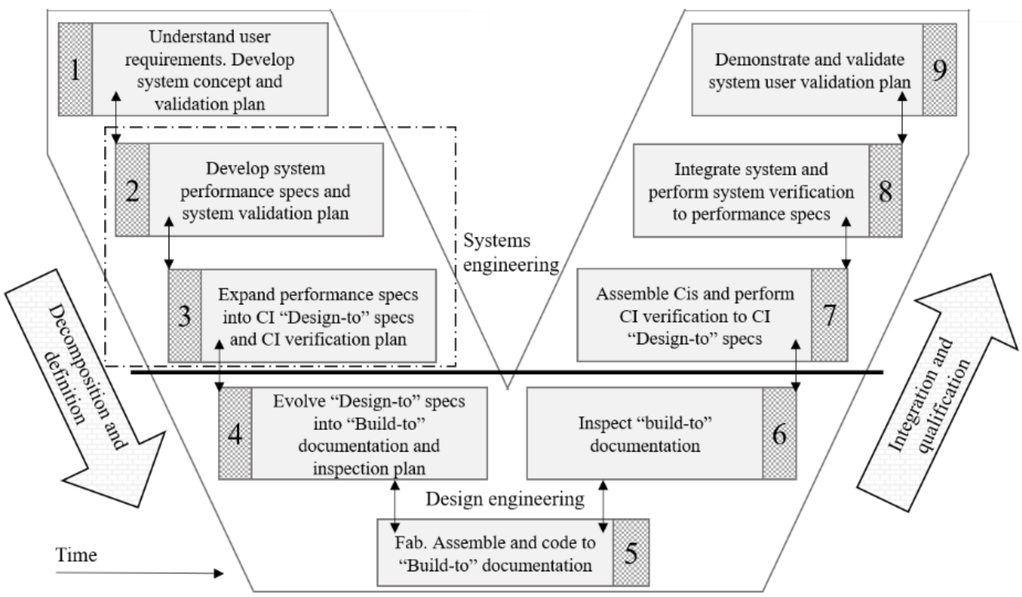


Figure 1.2. Thesis positioned in terms of the Vee model (Buede and Miller, 2016).

1.2. Research Questions

In this thesis, a model-based Design for Additive Manufacturing (DfAM) design support is presented to facilitate the introduction of AM in components for space applications. Additive Manufacturing technologies are attractive for space companies to, for instance, target new product functionalities or lower production costs. However, the lack of knowledge and experience in AM hinders its implementation in highly regulated industries such as the space industry. Based on this premise, the following research questions (RQ) are proposed:

RQ1*: What factors can foster or hinder (hamper) the introduction of AM as a manufacturing method for metallic component in space applications?*

RQ2*: How can (factors from RQ1) be modeled support the design for AM of metallic space components?*

The first question investigates the benefits and challenges encountered when introducing AM in space applications. The fact that the lack of AM knowledge hinders it implementation is a well-known fact in literature. In this context, one of the objectives of RQ1 is to shed light into what is meant by the expression "Lack of knowledge". In the same way, there is a general agreement up on the fact that AM technologies are attractive for space application. The other objective of RQ1 is to clarify in which ways is AM attractive for space applications.
The second question is focused on how the benefits and challenges identified in RQ1 can be modelled and included in a DfAM methodology for space products.

1.3. Thesis structure

The content and structure of this thesis is presented as follow. In Chapter 1 the main problem that motivated this research, the background, context and the research questions that this thesis aims to address are presented. In Chapter 2, the frame of reference is introduced where prominent research about DfAM for space applications is analyzed. In Chapter 3, the research methodology employed for conducting this research is presented. In Chapter 4, the four appended articles which are the backbone of this thesis are introduced, and their key results and findings are presented. The article findings introduced in Chapter 4 are discussed and used for answering the research questions in Chapter 5. The thesis is concluded in Chapter 6 where a conclusion of the thesis is presented, and future research activities are proposed.

2

FRAME OF REFERENCE

A concise description of the current state of the art of the research focus area.

2.1. The evolution of the space industry

According to Hobday (1998), space products can be classified as a complex product as they have high cost and value and are engineering-intensive with emphasis on design, project management and systems integration. Moreover, space products must withstand extreme launch and operation conditions and then operate under an autonomous and reliable way for periods that, in the case of satellite applications, can be extended to more than 15 years (Öhrwall Rönnbäck and Isaksson, 2018).
These requirements have shaped the space industry to be conservative with low production volumes and long development times, where traditionally, the main actors were governmental and defense agencies such as NASA, ESA or Roscosmos (Hiriart and Saleh, 2010).
During the early years of the space industry, technologies were developed in and for space applications and transmitted to other industries. However, nowadays, technologies are spinning into the space industry from other industries, helping to reduce costs and increase performance of many space applications such as telecommunications, Earth observation, and space exploration (Lal, 2016). The introduction of new technologies that allow performance increase and cost decrease, are key drivers for what is called as 'democratization of space', enabling the advent of companies primarily funded by private capital with a clear objective of increasing production numbers and lowering costs, challenging the traditional ways of space exploration, considered too expensive and time-consuming (Prasad, 2017; Martin 2014). These private companies are usually denominated "New Space" companies; some examples are SpaceX, One Web, Vector, Virgin Galactic or Planet Labs (Martin, 2014; Prasad, 2017; Lal, 2016). OneWeb, for instance, plans to shorten satellites manufacturing times and costs and has schedulled a large volume spacecraft production for a constellation of 900 satellites (OneWeb, 2019). Another example is SpaceX reusable rocket, achieving the re-flight of an orbital class rocket, SpaceX's Falcon 9 rocket (SpaceX, 2017).
It is estimated that in the next 10 years, around 10,000 New Space companies are expected to be started (Henry, 2016) and that the space economy will move towards getting civilianized and internationalized (Lal, 2016). Democratization of space is leading the space industry into an era of increased market competition and mass customization with a growing a need for cost and time to market reduction strategies.

To remain relevant in a competitive market, disruptive technologies such as Additive manufacturing (AM) are attractive for space companies to target new product functionalities or lower production costs, ensuring company permanence in the market and fostering new company capabilities (Loch and Kavadias, 2008).

2.2. Metal additive manufacturing in the space industry

AM is a strategic and radically new technology, which well combined with other technologies can generate promising businesses opportunities (Gibson, Rosen and Stucker, 2015). The recent advancements made in metal additive manufacturing (AM) technologies, are attractive for space components as the technology promises increased design freedom and reduced manufacturing costs enabled by efficient material allocation. For instance, AM allows for weight and material volume minimization, which are indeed drivers in costly products to be produced in low production volumes (Mellor et al., 2014). Taking advantage of the unprecedented design freedom enabled by AM, space products can be designed to achieve both weight and buy-to-fly ratio reduction as well as performance increase (Barnes, Kingsbury and Bono, 2016).

Unlike conventional manufacturing processes like formative (such as casting), subtractive (such as milling) or joining processes (such as welding), AM fabricates a physical object by material deposition layer-by-layer (Gibson, Rosen and Stucker, 2015).

Metal AM process are of special interest for the space industries as they can enable cost reduction and performance increase of high performance and heavy metal components such as manifolds or engine components. The different AM production processes for metals are categorized according to the material feed type (powder bed or beam deposition) and the heat source used for fusion (laser beam, electron beam, or plasma arc). A weldable metal alloy is a candidate for AM, on the other side, metal alloys that crack under high solidification rates are problematic for AM (O´Brien, 2018).

Researchers and industry practitioners agree up on the fact that the main challenge when implementing metal AM, is the lack of experience and the large amount of uncertainties and unknowns around the manufacturing process (Lindwall et al., 2017; O´Brien, 2018) which affects product design and development. First, there is a constrained material availability, non-established standards for machines and processes and undeveloped CAD software. Secondly, there is a lack of knowledge about the physical phenomena that take place during the AM process and a difficulty to predict the quality of a piece, as parts manufactured with AM have a complex thermal history that involves repeated fusion, directional heat extraction, and rapid solidification (Thompson et al., 2016; O´Brien, 2018).

AM manufacturing constraints and component quality are known to be dependent of the AM machine, process parameters, material and even product geometry, leading to part variability. Component variability affects mostly the introduction of AM in regulated industries such as aerospace, automotive or defense, as the introduction of AM in those industries, is highly correlated to certification and standardization (Gausemeie, et al., 2013).

At the current stage of AM maturity, Design for Additive Manufacturing (DfAM) methodologies for space products should acknowledge the lack of knowledge about how the physical phenomena and AM processes influence product design and product quality (Taylor, Manzo and Flansburg, 2016; O'Brien, 2018).

Moreover, when designing for AM (and new technologies in general), carried-over knowledge and practices related with traditional manufacturing processes can hinder the design process for AM. In the case of AM, traditional manufacturing constrains (such as avoiding designs with internal canals or intricate geometries when casting) are perhaps no longer valid for AM, and

at the same time, this new technology encompasses a new set of manufacturing constraints. The carried-over knowledge often leads to the development of AM products that are similar to their predecessors designed for traditional manufacturing technologies (Kumke et al., 2016; Seepersad, Allison and Sharpe, 2017).
In short, the recent advancements made in metal additive manufacturing (AM) technologies, render this technology attractive for space applications. However, new design mind sets are required to address the lack of knowledge about AM and mitigate the effects of carried over knowledge about traditional manufacturing technologies.

2.3. The need for multidisciplinary decision making in design for additive manufacturing

Due to the opportunities enabled by AM and the vast literature about DfAM methodologies (Boyard, 2015; Pradel et al., 2018), AM designs and design practices have evolved to lead to lighter and stiffer parts based sometimes in complex shapes that would be impossible to manufacture without AM. AM designs are in a great degree concerned with mass and cost reduction often achieved through part consolidation or topology optimization (Tang and Zhao, 2016; Orquera et al., 2017). However, although part consolidation leads often to weight reduction, it may hinder the ability to adapt designs to future requirements and to change and service components over time, thus increasing costs in the long term. Finding the balance between integral and modular architectures can be problematic, as it requires evaluating a series of trade-offs involving diverse multidisciplinary requirements (such as product adaptability, component interface costs, manufacturing costs or cost of post-processing activities).
There is an extensive literature about modularization/consolidation techniques (reviewed by authors such as Stjepandić et al. (2015) or Gershenson et al. (2004)), which are based on the collection of complementary or similar parts into modules, restricted by manufacturing constraints of complex geometries. These types of methodologies provide a multidisciplinary design approach to support decision making involving trade-offs across disciplines (such as adaptability, service ability, costs or manufacturability) in early phases of the design process. However, as AM allows the integration of functions that are impossible with other manufacturing techniques, modularization techniques implemented for traditional manufacturing technologies are not fully applicable for AM (Yang and Zhao, 2018).
The consequences of not having a multidisciplinary approach early in the design phases are often translated into costly redesign efforts and extended lead times (Otto and Antonsson, 1991; Sigurdarson, 2019). However, a problematic that rises from making such design decisions early (and which is independent of the technology implemented) is that the full set of information may not be available at these stages (Eppinger and Ulrich, 2011).
Nevertheless, the use of models in early phases of the product development (PD) process can facilitate design exploration and evaluation, understanding of the behavior of system elements, and validation, using the little information available at these early phases. Models can also serve as a mean for recording information and transmitting information and design decisions. Testing and validating system characteristics early, helps the premature detection and correction of design errors, when the time and financial impact of design modifications are minimum (Holt et al., 2016; Borky and Bradley, 2019).
Shortly, AM technologies enable great design opportunities but are often lacking a multidisciplinary view of the design requirements during early design phases. However, an early consideration of multidisciplinary requirements is problematic as information at these stages is scarce. To counteract the lack of information, models are implemented as they can

facilitate design exploration and evaluation, using the little information available at these early phases.

2.4. Model-based methodologies for design for additive manufacturing

Previous literature reviews about DfAM, presented by authors such as Boyard (2015) or Pradel et al. (2018), sustain that DfAM methods can be categorized in two groups: "opportunity-driven" methods, that focus on design freedom and aim to generate innovative geometries with new functionality, disregarding geometry manufacturability; and "manufacturing driven" methods, that perform minimal changes to a pre-existent component geometry to comply with manufacturing constraints of AM (Thompson et al., 2016). While the two approaches initially seem to be exclusive, they are often combined in diverse DfAM methodologies that integrate the benefits of AM with its manufacturing limitations (such as Boyard et al. (2013) or Salonitis (2016)). However, these methodologies tend to apply the manufacturing constraints at the detail design stage, for refining individual geometric features (Pradel et al., 2018). Previous research (Huang et al., 2007) suggests that, as knowledge about AM processes and AM manufacturing constraints is limited but in constant evolution, model-based design methodology that include constraints modelling early in the design phases (before detail design) can support the efficient management and use of that knowledge.

However, manufacturing constraints are not the only constraints in a product design process that should be considered and modeled. Multidisciplinary constraint about the development and behavior of a system (non-functional requirement, NFR) are critical for developing a successful product design and should be introduced as soon as possible in the design phases, such as requirements on performance, reliability or scalability (Huang et al., 2007). Although not yet widely applied in DfAM, constraint-based modelling is popular among software design methodologies. Authors such as Bosch and Molin (1999) or Mylopoulos et al. (1992) proposed model and constraint-based design methodologies, implementing function modelling techniques for including non-functional requirements in the early design of software systems. Their approaches support organizing, analyzing and clarifying NFRs, for analyzing the complex trade-offs that need to be made during design and for developing risk mitigating strategies. They also provide a way to deal with changes in requirements and design assumptions, providing a rich representation of the relationships between non-functional requirements and product functional requirements.

In summary, model-based design methodologies able to model multidisciplinary constraint are critical for developing a successful product design and should be implemented as soon as possible in the design phases. Constraint modelling is particularly relevant in the introduction of AM in space components, as it can help dealing with the changes in requirements and design assumptions that come naturally from a technology that is still under development.

2.5. Function modelling

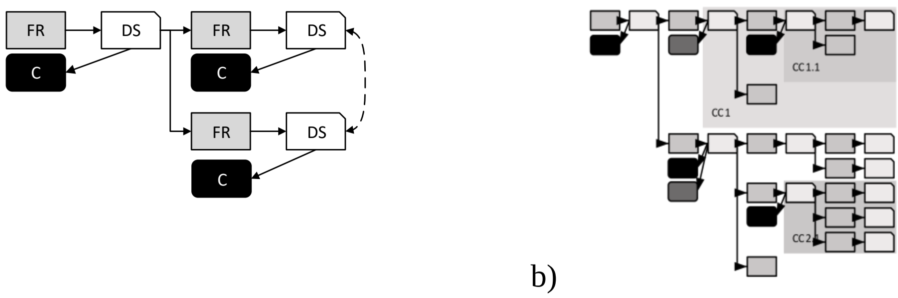
Function modelling has been proven useful among the constraint modelling methodologies mentioned in the previous section. Their main advantage is the systematic arrangement of system information to support designers in making decisions about product architectures and manage complexity in multi-technology environments (Eisenbart et al., 2011). In this thesis, a function is defined as "intended behavior", although there is no unique definition of the term in literature. In a function model, the main product function is first identified and then the complete product system is decomposed in sub-functions which are hierarchically arranged in a function three (Erden et al., 2008).

For helping the designer to identify and understand the functional relationships of the design, multiple “function representations” have been developed. These function representations aim to facilitate the connection between an abstract system concept (system architecture) and the physical design (Eisenbart et al., 2011).

There are a wide variety of function modelling techniques, such as the one proposed by Weilkiens using the description language SysML combined with modelling tools like UML (Weilkiens, 2007), the widely applicable function-behavior-state model (FBS) for modelling a system with its functional descriptions (Umeda et al., 1990), or the functions template strategy adopted by Heller and Feldhusen (2014) for creating unambiguous function structures. These types of modelling techniques link functional requirements with product design features and can incorporate in the model different types of interactions among design features (material, signal, energy, geometry), providing a modelling support to be used across disciplines.

Such is the example of the function modelling technique EF-M (enhanced function means). In this technique a hierarchical product structure (Johannesson and Claesson, 2005) that associates functional requirements (FR) with design solutions (DS) to perform those functions, which can be subject to design constraints (C) is provided. Design solutions can be modelled on their interaction with each other via geometry, signals, energy or material flow as well. The mentioned modelling elements are illustrated in Figure 1.a. The design rationale that is created through this structure iterates between FR and DS. This structure, illustrated in Figure 2.1.b, allows to identify the impact of constraints, as well how a change in a function or constraint affects the product structure. Moreover, to enable a segmentation of the product structure, Configurable Components (CC) are implemented in EF-M as well. CC, introduced by Claesson (2006), are objects that encapsulate an entire branch (DS and sub-elements) of an EF-M tree, as shown in Figure 2.1b.

In summary, function models help understanding product architecture and can enable the representation of constraints in early phased of the PD process. For dealing with the changes in requirements and design assumptions that come naturally from a technology that is still under development, constraint modelling is critical.



a) b)

Figure 1. EF-M modelling, a) modelling elements, based on (Johannesson and Claesson, 2005) and b) levels of EF-M tree based on (Claesson, 2006) and encapsulation through CC.

3

RESEARCH APPROACH

A description about the research approach followed

3.1. Research context

Most of the content presented in this thesis was developed in the context of the research project RIQAM, with financial support from Rymdstyrelsen, Swedish National Space Agency (Rymdstyrelsen, 2019). RIQAM (Radical Innovation and Qualification for Additive Manufacturing) is an industrial project is a collaboration of Chalmers University of Technology with Luleå University of technology and three major companies manufacturers of space components in Sweden, GKN Aerospace Engine Systems (GKN, 2019), RUAG Space AB and OHB Sweden AB (OHB, 2019). The project has the purpose of demonstrating the potential of AM for space applications. Moreover, it aims to identify changes in the PD process required to implement AM in space products and the necessary qualification activities.

Discussions about the implementation of the presented design support for the introduction of other technologies in the space industry (included in later sections of this thesis) were developed in the context of the project CHEOPS. CHEOPS (Consortium for Hall Effect Orbital Propulsion System) is a project founded by the European Union's Horizon 2020 research and innovation program, with the participation of more than 10 European aerospace companies (such as Thales Alenia Space France/Belgium, Airbus SAS or Safran) and the University Carlos III of Madrid. This project proposes to develop three different hall effect thruster electric propulsion systems, each with different application fields and orbits.

Insights about digitalization and industrialization of AM processes will be included in future research activities, in the context of the project IDAG (Infrastructure for Digitalization enabling industrialization of Additive manufacturinG) (Kunskapsformedlingen, 2019).

3.2. Research framework

Research can be defined as a "Systematic and logical study of an issue or problem or phenomenon through a scientific method" (Krishnaswamy and Satyaprasad, 2010). Different research methodologies are chosen to address research gaps and research questions; an appropriate research methodology should enable data collection to answer the research questions.

The different studies that lead to this thesis can be organized in a research framework which is based on the Design Research Methodology (DRM) proposed by Blessing and Chakrabati

(2009). The aim of this framework is to create understanding of certain phenomena as well as to improve them. The DRM framework is composed of four iterative basic stages, represented in Figure 3.1: 1) Research clarification, for identifying and clarifying the research problem; 2) Descriptive study I, through empirical studies the understanding of the research problem is increased; 3) Prescriptive study, where methods to address the research problem are developed and applied; 4) Descriptive study II, where the impact of the proposed method is evaluated.

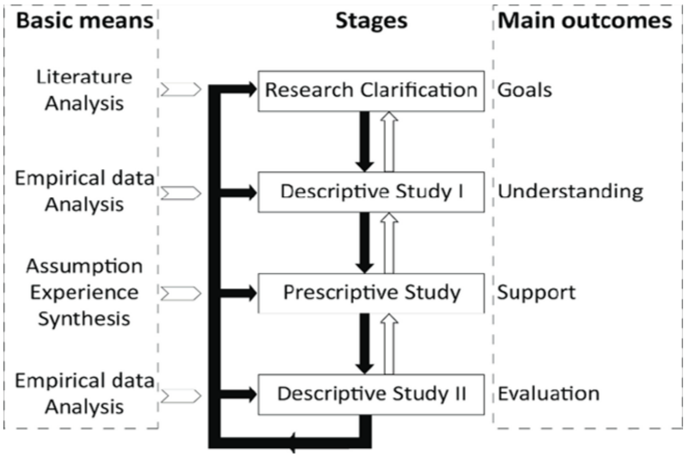


Figure 3.1. Design Research Methodology (DRM) framework (Blessing and Chakrabarti, 2009).

Each of the four appended articles in this thesis has contributed to different stages of the DRM framework, their contribution is exhibited in Figure 3.2.

Moreover, the research activities were conducted in the context and concurrent with the RIQAM project that enabled practical understanding of the state of the art of the design practices implemented in the space industry. In fact, the case studies presented in the articles were based on components from RIQAM and verified in terms of fidelity with the industry specialists.

The research in the thesis started with a systematic literature mapping around DfAM methods and design practices in the space industry (Article A). The aim of this article was to research how can a DfAM methodology support the introduction of AM in space components considering benefits and limitations of this technology. Thereafter, in the RIQAM project, empirical studies begun through a series of workshops were practitioners from industry, Luleå University and Chalmers University of Technology attended. In those workshops, it was possible to directly observe three different space products being designed for AM. Article B, C and D are based on the empirical results obtained from those workshops. In Article B, the first part of the DfAM design support presented in this thesis is proposed, reflections about its application in the context of RIQAM are presented as well. In article C a modularization methodology for space products manufactured with AM is proposed; this article is considered the second part of the DfAM design support of this thesis. Article D describes the state of the art of qualification procedures in the space industry and its content is going to be used to enrich the design support.

Figure 3.2 illustrates the contribution of the appended articles according to the DRM framework.

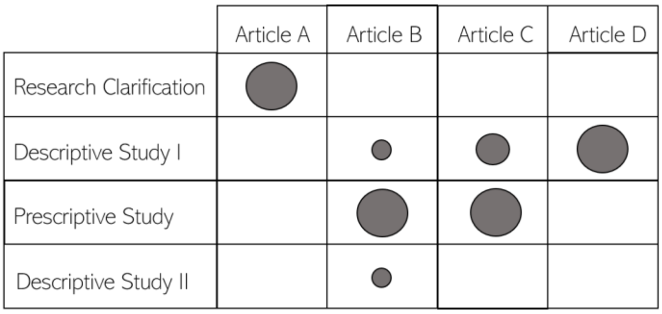


Figure 3.2. Positioning of the thesis articles according to the DRM framework.

3.3. Data collection procedures

As the research activities have been performed in the context of the RIQAM project, each article was developed in close collaboration with industry practitioners. The data collection activities were the following:

Literature review

In every article, a short literature review about the state of the art of the research area of interest is presented. The academic publications used in the literature reviews were found using keywords on the SCOPUS database and backward and forward snowballing (Wohlin, 2014) procedures from well-known articles in the field. Due to the fast pace of the AM technology development, non-academic publications retrieved from technology websites and forums were also included.

Larger literature review activities were performed for the Research Clarification Study in Article A to identify and evaluate existing areas or gaps demanding research (Wohlin, 2014). In this article, a systematic literature mapping (Kitchenham and Charters, 2007) was performed by cross-analyzing and 'matching' two neighboring research areas (research on design for additive manufacturing methods, and research on the introduction of AM in space products). From the different methodologies for performing a literature review, a literature mapping study was preferred, as this methodology focuses on broad research questions reviewing substantial number of publications, aiming for publication classification to achieve a high understanding of the research area (Barn et al., 2017). The entries obtained through SCOPUS, snowballing and non-academic publications were filtered by title, abstract and then by full-text content, based on appropriate inclusion criteria.

Workshops

Most of the data gathering activities for Articles A, B, C and D were performed through workshops for the project RIQAM, that joined the efforts of Swedish universities and aerospace companies. The distribution of data gathering, and validation activities through the workshops is presented in Figure 3.3. These workshops followed the action research (AR) methodology, a proven methodology for understanding ill-defined problems in complex organizations that describes how changes in practice can positively impact the 'community of practice' (Avison et al., 1999). A total of five workshops and five follow-up meetings attended by ten experienced industrial practitioners from the participating companies, were performed. The workshops were held approximately once every two months with follow-up meetings held between workshops for data and model validation purposes. The industrial participants were engineers (with 12 to

30 years of experience) working in product development at the participating companies. Observations and workshops results were documented through field notes and pictures and transcribed and analyzed through content analysis (Miles et al., 2013). Observations and results were then distributed to the participants of the workshop for discussion. Follow-up phone meetings were conducted with the participations for verification and exchange of statements.

The first workshop (W1) focused on presenting to the participants ten designs for AM strategies, (such as part consolidation or topology optimization) using examples. These strategies are summarized in Lindwall and Törlind (2018). The presentation of these strategies acted as random stimuli (Cross, 2000) for the generation of novel concepts. Each company presented one case study product to be redesigned for AM during the five workshops. During concept generation phases of the workshops, no designs for AM methodology was implemented, in order to mirror the current design activities in the three involved companies (which are not supported by formal design for AM processes). A series of semi-structured interviews (Robson, 2002) were conducted in between the workshops, to understand the participant´s own experience designing for AM and use those insights to further develop workshop activities. In the second workshop (W2), function modelling techniques were implemented for continuing the design process. The workshop focused on functional decomposition of the different case studies. Observations and studies from W1, W2 and their complementary meetings were utilized for the development of Articles A, B and C. Observations from W2 were also implemented in the development of Article D.

Function models were developed with the function decompositions from W2. These models were created collectively between the researchers and industrial partners during complementary meetings and were validated and refined during the third workshop (W3). In W3, results from Articles A and B were presented and discussed as well, for validation purposes. The rest of W3 was dedicated to discussions and reflections for developing Article D.

Article C features the redesign of a satellite antenna, in the fourth workshop (W4), the antenna redesign was presented and validated by the workshop participants, moreover, a modularization exercise was performed. In the exercise, participants reflected up on the results from Article C and discussed benefits and constraints of modular architectures. In W4, a plan and schedule for the data collection activities for Article D was established.

In workshop 5, Article D was presented and discussed to validate its results.

	Article A	Article B	Article C	Article D
Workshop1	D	D	D	
Workshop 2	D	D	D	D
Workshop 3	V	V		D
Workshop 4			V D	
Workshop 5				V

Figure 3.3. Data gathering, and validation activities performed during the RIQAM workshops for the different articles in this thesis.

Interviews

For refining specific points and concerns lifted during the workshops, semi-structured interviews (Robson, 2002) with industrial practitioners were performed for Article C and Article D. Most of the subjects interviewed were not participating in RIQAM, although they belonged to the participating companies. Semi-structured interviews were preferred since the topics in study are complex and can be interpreted in various ways, requiring lengthy explanations and follow up questions (Bryman and Bell, 2015). The interviews were performed following a set of pre-defined questions; however, the interviewees were encouraged to not just answer the questions but also to go in-depth on specific points that they considered pertinent (Williamson and Bow, 2002).

When interviewees granted permission, the interviews were recorded and then transcribed, otherwise, data were collected through notes. To clarify the data and identify recurring themes, selective coding was implemented. Data reduction in the form of pattern matching and data displays was utilized to synthesize the findings (Miles and Huberman, 1994). The pattern matching involved the definition of categories based on topics identified before performing the interviews. The interviews transcripts were read, and quotes related to those categories were highlighted. The result from the coding was compiled in spreadsheets for comparison purposes. The quotes in the spread sheet were then condensed into a text document which was then send back to the interviewees for validation purposes.

4

SUMMARY OF APPENDED ARTICLES

A concise and descriptive summary of results obtained in the four appended articles

4.1. Article A: Impact on design when introducing Additive Manufacturing in space applications

Article summary

In this article the impact on the design process when introducing additive manufacturing in space components is studied. Through a systematic literature mapping and an empirical study, the limitations and challenges of introducing AM in space components are matched together with the existing design strategies for additive manufacturing. The article points at “modelling” as a crucial design strategy in the context of DfAM.

From the systematic literature mapping and the empirical study is inferred that there is a lack of knowledge, technology development and experience regarding the application of AM in space components.

During the empirical study, the largest manifested concerns were regarding quality and qualification: nature and detection of manufacturing defects and their impact on performance, material behavior and capabilities, surface finishing and geometric accuracy. Unfortunately, it seems to be a misalignment between the industry needs and challenges and the general focus of the design research community. It is inferred that for AM to be introduced in space applications, space components should go through a process of redesign. However, even if AM enables design freedom, practitioners exhibit a tendency to design products similar to those they know. Moreover, AM design freedom is not total, as this technology has several manufacturing limitations.

It is concluded from the findings that when designing for a new manufacturing technology, modelling techniques are of importance to exploit design exploration opportunities and to gain confidence in decision making. Systematic modelling techniques, such as function modelling (one out of three DfAM methodologies implement function modelling), can be a powerful support for organizing and implementing the little information available about a product and a technology. Implementing these techniques, available knowledge about AM can be used for extracting conclusions and analyzing the proposed concepts, enabling concept comparison.

Moreover, as the product representation is abstract rather than physical, these techniques are suitable for early phases of the design process.

Conclusions

For introducing AM in space applications, space components should go through a process of redesign. However, even if AM enables unprecedented design freedom, this freedom is not total, as this technology has several manufacturing limitations. Moreover, there is a lack of knowledge, technology development and experience regarding the application of AM in space products. These results are in agreement with several articles in the topic such as (Salonitis, 2016; Lindwall et al., 2017; Dordlofva, 2018). This lack of knowledge and experience lead to designs that that are similar to their traditionally manufactured predecessors, not taking advantage of AM design freedom.
When designing for a new technology, model-based design techniques can contribute to design exploration and to gain confidence in decision making. Although, as other authors remarqued as well (Lindwall et al., 2017; Dordlofva, 2018; O´Brien, 2018), to be relevant in the space industry, design techniques must have a holistic approach to product development and product lifecycle to consider early in the design phases the needs of later PD process activities such as qualification.

Contribution to the thesis

The research performed in this article served for identifying the research gap for this thesis and for gaining a better understanding of the space industry and DfAM. The article points out that when designing for a new manufacturing technology, model-based design techniques are of importance to exploit design exploration opportunities and to gain confidence in decision making. As information is scarce in early phases of the design process, abstract product representations (such as function models) can facilitate the design process.

4.2. Article B: Constraints replacement-based design for Additive Manufacturing of satellite components.

Article summary

In this article, as a basis for product redesign using additive manufacturing, a methodology based on EF-M function modelling methods and constraint modelling is proposed. In this methodology, to redesign a product that is currently manufactured with traditional manufacturing methods, its original functions, design solutions and manufacturing constraints are identified. Then, the original manufacturing constraints are removed and replaced with manufacturing constraints for AM. Hence, the design space is freed and then constrained again according to AM limitations. From this process, a new AM function model is developed and utilized for designing a new part geometry for AM. The newly designed product is then manufactured.
This methodology has been applied on a case study featuring a satellite sub-component.
The outcome of this study is a design methodology for taking advantage of AM design freedom, while considering manufacturing constraints early in the design phase.
As the constraints are related to the AM process chosen, different AM processes present different constraints. In this methodology, constraints are divided in two groups: manufacturing constraints (Cm, related to the manufacturing process) and functional constraints (Cf, related to the performance the product is supposed to achieve). The process of constraint distinction

facilitated the process of identifying the DS in the design that are only manufacturing dependent and that can therefore, be redesign for AM.

Conclusions

The methodology proposed in this article aims at redesigning components for AM, taking advantage of AM design freedom but considering AM manufacturing limitations as well, as suggested by authors such as (Boyard, 2015; Pradel et al., 2018).
Function modelling methodologies allow an organized display of product information than enables a deep understanding of product architecture. The nature of EF-M modelling techniques permits the identification and separation of design constraints that depend on product performance from constraints that depend on the manufacturing process. This separation provides the designer with an effortless identification of the product features and geometry that are manufacturing dependent and can, therefore, be redesigned for AM. Moreover, the process of identifying traditional manufacturing constraints and then replacing them with AM constraints can support the acknowledgment and enable the removal of the carried-over knowledge and experience that designers have about traditional manufacturing technologies. As suggested by the work of (Kumke et al., 2016; Seepersad et al., 2017) acknowledging carried-over practices can be the first step towards mitigating the practitioners´ tendency to design products similar to those they know.

Contribution to the thesis

The research performed in this article served the purpose of developing and testing a model-based DfAM methodology for space components. The methodology is based on function and constraint modelling, as their abstract product representation is suitable for early design phases where product information is scarce. Moreover, their level of abstraction facilitates model evolution and adaptation, as knowledge about AM technologies and constraints continues to be developed.

4.3. Article C: Modular product design for Additive Manufacturing of satellite components: Maximizing product value with optimization algorithms.

Article summary

In this article the development of a methodology to support multidisciplinary design decisions related to part consolidation and modularization in space products designed for AM is presented. For space manufacturers, additive manufacturing promises to dramatically reduce weight and costs by means of integral designs achieved through part consolidation. However, integrated designs hinder the ability to change and service components over time (increasing costs), which is instead enabled by a highly modular design. Finding the optimal balance between integral and modular designs in additive manufacturing is of critical importance. However, making design decisions involving several trade-offs is problematic for designers without experience in AM. The product modularization methodology proposed in this article supports decision making about such trade-offs. The methodology combines function modelling and Design Structure Matrices (DSM) with an optimization algorithm. The algorithm maximizes a value function that takes into consideration product adaptability to future requirements, module interface cost, product weight and post-processing costs when designing for AM. The modularization methodology was derived from data collected through the RIQAM project. During this empirical study, the difficulty of assessing modularity when designing for AM in space products and the tendency for part consolidation motivated the development of this methodology. The participants of the study stated that for effectively redesigning for AM, interactions between product functions, components and interfaces should be established early in the design process. The implementation of the methodology was demonstrated in a case study featuring the redesign of a satellite antenna.

The convenience of the antenna design resulting from the application of the methodology has been acknowledged and supported by companies participating in the workshops. Considering design for adaptability perspectives, the methodology facilitates the design of a product with a longer product service life and increasing return on product investment. The incorporation of manufacturing costs into the analysis allows designers to account for weight reduction benefits needed in space products. Furthermore, including post-processing costs into the analysis helps addressing geometry feasibility and manufacturing constraints of product architecture, which is a feature frequently missing in DfAM methodologies. This article points out as well that in the case of AM, product part consolidation and weight reduction are not necessarily related to a reduction of material consumption.

Conclusions

Finding the optimal trade-off between integral and modular designs is of critical importance and is a topic widely discussed in literature (Gershenson et al., 2004; Stjepandić et al., 2015). However, when designing for AM, designers exhibit a tendency to consolidated designs, disregarding sometimes the benefits of modularity. Due to the lack of experience in design for AM, making design decisions involving several trade-offs is particularly problematic for AM designers. The identification and organization of the interactions between product functions, components and interfaces should be established early in the design process. To assess product modularity, trade-offs concerning a holistic regard of product development/product life cycle must be considered, such as adaptability to future requirements, manufacturability and manufacturing costs. These results are well aligned with literature presented by (Engel et al., 2017; Yang and Zhao, 2018).

Contribution to the thesis

The research performed in this article served the purpose of developing a methodology to support multidisciplinary design decisions related to part consolidation and modularization in space products designed for AM. Implementing function models and company data about previous versions of a product, a modular AM product architecture can be envisioned in early design phases, considering multidisciplinary design requirements.

4.4. Article D: Drivers and Guidelines in Design for Qualification using Additive Manufacturing in Space Applications

Article summary

In this article, factors that impact or drive the qualification activities of products for space applications are presented. These factors are denominated “qualification drivers” and are intended to serve as a baseline for, in the future, developing design guidelines for supporting qualification of AM components. The results presented in this paper are based on 12 semi-structured interviews with two companies that manufacture space products in the European space industry. From this article, it is concluded that the market shift that the space industry is experiencing impacts on the PD processes. Introducing AM in their portfolio, companies aim for design flexibility, cost and time to market reduction, and an increase in production volume while maintaining a high product quality. However, the knowledge about AM capabilities is scarce and the product outcome is sometimes unpredictable, which renders the qualification activities challenging and expensive.

Qualification is an integral, but expensive, part of product development in the space industry. For mitigating time-consuming and expensive qualifications activities for AM, qualification logics should be included and consider as a design guideline during the early design processes. Unless the qualification activities/strategies are defined when design decisions are made, the cost of qualification might become too large.

A DfAM methodology for the effective introduction of AM in the space industry must include Design for Qualification guidelines to assist designers to deal with critical product features. The qualification drivers proposed in this article support the future development of qualification guidelines. However, even if the qualification drivers are general enough to be applied to multiple products and business cases, there will not be one qualification logic that fits every AM component, as qualification is product and process dependent.

Conclusions

As previously reported, the market shift that the space industry is experiencing motivates the introduction of new technologies such as AM. Introducing AM, companies aim for design flexibility, cost and time to market reduction, and an increase in production volume while maintaining a high product quality. However, the knowledge about AM capabilities is scarce and the product outcome is sometimes unpredictable. As qualification is an integral part of product development in the space industry, qualification activities must be considered early in the design process. Otherwise, due to the lack of knowledge and experience regarding AM, the cost of AM qualification might become too large. These results are aligned with previous literature on the field of qualification for AM in space components (Dordlofva, 2018; Dordlofva and Törlind, 2018; O´Brien, 2018).

Contribution to the thesis

The research performed for this article evidenced that the knowledge about AM capabilities is scarce and the product outcome is sometimes unpredictable, which renders the qualification activities challenging and expensive. The early modelling of qualification requirements can help mitigating the cost of these activities.

5

RESULTS

Answers to the research questions

5.1. RQ1- Factors that foster or hinder the implementation of AM for space applications

As interviewees stated (Article D), the market shift that the space industry is experiencing impacts the PD processes. Introducing AM in their portfolio, companies aim for design flexibility, cost and time to market reduction, and an increase in production volume while maintaining a high product quality. However, the knowledge, experience and technology development in AM is scarce and the product outcome is sometimes unpredictable. This result is aligned with the literature studies performed in Article A and the results of the empirical studies from Article C.

From the literature review (Article A) it is concluded that the research area related to AM is in constant grow, however, the areas of interest of the industrial and academic domain are misaligned. The industrial domain seems mostly interested on developing modelling strategies to facilitate qualification and quality assurance activities; while the academic domain is mostly interested in developing methodologies for design exploration. The main difference of these two approaches is that design exploration methodologies aim to take advantage of AM design freedom and are often not concerned with important drivers for qualification and quality assurance such as manufacturability of mechanical properties. Both the workshops performed in the context of RIQAM and the interviews performed from Article D, sustain that qualification and quality assurance procedures (nature and detection of manufacturing defects and their impact on performance, material behavior and capabilities, surface finishing and geometric accuracy) are important obstacles to overcome for introducing AM in space components.

Moreover, for a meaningful implementation of AM, the components should go through a process of geometrical redesign (Articles A, B, C and D). However, the redesign of components for AM is problematic as practitioners exhibit a tendency to design products similar to those they know, even if AM enables design freedom (Articles A and D).

Moreover, the studies pointed to the fact that AM design freedom is not unlimited, as this technology has several manufacturing limitations (Articles A, B, C and D). The most discussed AM limitations are post-processing activities (such as removal of support structures), manufacturing constraints (such as minimum feature size), undeveloped CAD software (lack of AM material libraries, lack of support structures analysis in design software, etc..), or lack of standards and material availability (Article A). Moreover, AM constraints are dependent on the AM machine, machine parameters, material, powder quality and product geometry (Articles B, C and D). Due to this dependence, design strategies and guidelines found in literature might not be applicable to specific design set-ups, which hinders decision making activities.

DfAM methodologies are one of the major focus of the AM academic research (Article A). As other authors have stated (Boyard, 2015; Pradel et al., 2018), many DfAM methodologies tend to focus either on AM design freedom or on AM limitations, but successful DfAM methodologies focus on both aspects (Articles A and B).

However, due to the possibility of reducing weight through part consolidation, a design aspect that is often forgotten in literature about DfAM is modularization (Article C). Moreover, there is a gap in the literature concerning when it is convenient to consolidate components into a single AM module and when it is not. As presented in Article A, one third on DfAM methodologies are oriented to part consolidation focusing on weight and volume reduction disregarding the benefits of modular components. This result was supported by the findings from Article C, where workshop participants exhibited a tendency to part consolidation for attaining weight reduction (Article C).

Although part consolidation leads to weight reduction, it may hinder the ability to adapt designs to future requirements and to change and service components over time, thus increasing costs in the long term.

For these reasons, when designing for AM, it is of critical importance to find a balance between integrality—achieved through part consolidation—and modularity. However, finding this balance is challenging for unexperienced AM designers, as it requires evaluating a series of multidisciplinary trade-offs such as product adaptability, component interface costs, manufacturing costs and cost of post-processing activities.

5.2. RQ2 - Multidisciplinary modelling to support DfAM in space application

From the literature review findings (Article A) it is concluded that the main modelling techniques implemented in DfAM methodologies can be categorized as: function modelling (54%), geometrical modelling (43%) and mathematical/physical modelling (3%).

Preliminary empirical findings indicate that the abstract product representations provided by function modelling techniques are suitable for early design phases where product information is scarce (Articles A, B and C). Moreover, regarding industry concerns about quality and qualification procedures, function modelling representations can support the identification of critical ‘product features´ that can influence product quality (Article C).

Article B proposes a DfAM methodology based on function modelling and a constraint replacement procedure. In this article, a distinction is made between Manufacturing constraints (Cm) and Functional constraints (Cf):

1. Cms depend on the manufacturing process, such as minimum manufacturable wall thickness.
2. Cfs depend on functional requirements, such as the minimum wall thickness necessary to cope with a certain fluid pressure.

This distinction between constraints facilitates the process of identifying the DS in the design that are only manufacturing dependent, and that can therefore, be targeted to be redesign for AM. Moreover, the process of identifying traditional manufacturing constraints and then replacing them with AM constraints can also support the acknowledgment and enable the removal of the carried-over knowledge and experience that designers have about traditional manufacturing technologies. Acknowledging carried-over practices can be a first step towards counteracting the practitioners´ tendency to design products similar to those they know.

As AM challenges current design practices due to its sensitivity to and interaction among process parameters and their interaction with design configuration, AM manufacturing constraints are machine, machine parameters, material and geometry dependent. For this reason, the AM manufacturing constraints that are found in literature are not fully applicable to every design scenario. Moreover, manufacturing parameters such as build orientation, affects anisotropy, surface roughness or porosity in ways that are not fully understood or documented yet in literature (Articles A and D).

Insights from Article D point out that to mitigate time-consuming and expensive qualifications activities for AM, qualification logics should be included and consider as design guidelines during the design process. These qualification logics can be included in the shape of constraints regarding aspects such us material properties, design margins or inspect ability. Moreover, as qualification is product and process dependent, the flexibility of the modelling strategy proposed in Article B enables the inclusion and evolution of constraints associated to qualification processes.

These results point to the fact that function modelling techniques are appropriate for DfAM methodologies for space components, as carried-over knowledge can be mitigated (therefore enabling a batter implementation of AM design freedom) and quality and qualification concerns can be addressed early in the design phases.

However, this technique alone does not address the tendency to part consolidation observed during empirical studies from Article C. As discussed in the previous section, part consolidation leads to weight reduction, but it can hinder the ability to adapt designs to future requirements or to change and service components over time, thus increasing costs in the long term. Products are designed to fulfill more than one objective, and when designing for traditional technologies practitioners can sometimes rely on their own experience to make multi-objective design decisions. However, as knowledge and experience about AM are limited, modelling approaches to support multi-objective design decision making processes are necessary for DfAM. Article C proposes a modularization methodology that supports designers finding the product architecture with the highest value regarding product adaptability to future requirements, module interface cost, product weight and post-processing costs when designing for AM. The modularity methodology is based on a combination of function modelling techniques and an optimization algorithm. For populating the product FM, extensive information is gathered, however, this information is useful for assigning some exclusion criteria for components that should not be merged. The methodology does not consider costs of quality inspection and qualification procedures, however, these aspects are considered in the exclusion criteria, as merging some components could interfere with inspection or qualification activities.

6

DISCUSSION

A discussion and interpretation of the thesis results relative to the state of the art of AM technologies for space applications.

To introduce AM in the space industry and take advantage of its benefits such as weight reduction or performance increase possibilities, several obstacles must be overcome. The results from this thesis point out that those obstacles can be generalized as: lack of knowledge and experience, and lack of technology development.

These obstacles contribute to the main reason why space manufacturers are sometimes reluctant to the implementation of AM. The lack of knowledge and technology development lead to a lack of predictability and repeatability of the results, which render qualification activities expensive and problematic. These results are aligned with previous literature about obstacles and challenges for the implementation of AM in the space industry, such as (Lindwall et al., 2017; Dordlofva, 2018; O´Brien, 2018). Other consequence of the lack of experience in AM and the extensive experience about traditional manufacturing technologies, is the design of AM component that are similar to their traditional predecessors.

In this thesis, a model-based Design for Additive Manufacturing (DfAM) design support is presented to facilitate the introduction of AM in components for space applications. The methodologies implemented in this thesis aim at redesigning components for AM, taking advantage of AM design freedom but considering AM manufacturing limitations as well. This procedure is aligned with results presented by Pradel et al. (2018), that concluded that beyond design freedom, engineers are interested in manufacturability. In this sense, this work is similar to current approaches such as Boyard (2015), that proposed that the design should be developed concurrently with AM process analysis to create manufacturable designs.

The implemented methodologies try to mitigate the negative effects that AM lack of knowledge and experience have on the design practices. For instance, there is a vast literature about modularization techniques (reviewed by authors such as Gershenson et al. (2004) or Stjepandić et al. (2015)), which are based on the collection of complementary or similar parts into modules, restricted by manufacturing constraints of complex geometries. AM, however, allows the integration of functions that are impossible with other manufacturing techniques. For this reason, modularization techniques implemented for traditional manufacturing technologies are not fully applicable for AM (Yang and Zhao, 2018).

Yang and Zhao (2018), who are among the pioneers of modularization for AM, analyzed traditional modularization rules and adapted them for AM. Their strategy, systematic and easy to apply, is designed to exclude infeasible design solutions and to support part consolidation decision-making in the early stages of the design process. Their work was further expanded

(Yang et al., 2019), with a numerical approach for the identification of components to consolidate. This approach is a reliable support for making modularization decisions in complex products and can be (theoretically) applied to any product. However, these general methodologies are not tailored to the space industry and therefore do not consider important design trade-offs of space products, such as weight reduction and adaptability to market changes. The AM modularity methodology presented in this thesis is novel in the sense that it supports space components designers to make design decisions concerning multidisciplinary requirements, at early stages of the product design process.

However, the main contribution of the DfAM design support introduced in this thesis is related with constraints modelling, classification and replacement.

As constraints can be defined as non-functional requirements (NFR), constraint modelling enables the acknowledgement and visualization of NFR, aiding the designer to constrain the design space.

In this context, function models serve as a means for information storage, documenting the associations between FRs, DSs and Cs which can serve as a sort of database for future designs, increasing AM documented knowledge. As AM constraints are machine dependent, early constraint modelling efforts can support decision making procedures about future machine purchases and technology development activities. The early consideration of constraints about the development and behavior of a system is considered critical for product success by authors such as (Huang et al., 2007). Moreover, the work presented by Boyard, (2015) or Pradel et al. (2018) state that successful DfAM methodologies take advantage of AM design freedom considering AM manufacturing limitations (constraints) as well, early in the design process.

When making decisions, novel design alternatives are often compared to a base reference design, where a solid experience and confidence exists. Novel designs need to be proven to be "better" in comparison with existing solutions and these decisions have to be made early (already on a concept level), where design changes can be made spending less time and effort. Function modelling techniques can support the process of comparing new designs with previously existing ones as well, due to the possibility of representing different alternatives for a DS in the same function model. The downside of making decisions early is that the full set of information may not be available at these stages, constraint modelling can aid the process of front-loading early design phases with information (translated into constraints) to assess the "goodness" of new designs. For instance, including qualification constraints in early design phases can enable a shorter time to market product development and decreased design and qualification costs.

The results in this thesis suggest that the abstract product representations provided by function modelling techniques are suitable for early design phases where product information is scarce. Moreover, these techniques support the introduction of new product functionalities and technologies. This result resonates well with literature proposed by other authors such as Levandowski et al. (2013) that implemented technology and function-based configurable product platforms for the design of complex systems in the early design phases; or Landahl et al. (2018) who state that the level of abstraction of function models enables the incorporation of new product functions and the adoption of new technologies.

The process of identifying traditional manufacturing constraints and then replacing them with AM constraints can support the acknowledgment and concretization of carried-over knowledge about traditional manufacturing technologies. Therefore, enabling its removal and replacement with AM design insights.

As several authors (Kumke et al., 2016; Seepersad et al., 2017) suggest, when practitioners design for AM, they are often designing a product for which the current known designs are manufactured with traditional manufacturing processes. With this background, it is expected to fixate on conventional design solutions and geometries hindering the design of solutions that take advantage of AM design freedom.

Acknowledging carried-over practices can a first step towards mitigating the practitioners´ tendency to design products similar to those they know.

The flexibility of constraint modelling allows a holistic regard of the PD process, considering the whole product life cycle in the early design phases. This holistic regard is possible as constraints about, for instance, qualification activities, post processing, manufacturing or recycling, can be modeled and included in the FM tree enabling a multidisciplinary design approach. The early modelling of constrains with a holistic regard of the PD process and product life cycle is currently implemented in other industries such as the software industry, by methodologies like the ones presented by (Mylopoulos et al., 1992; Bosch and Molin,1999; Huang et al., 2007). Their approaches support organizing, analyzing and clarifying non-functional requirements (constraints), to analyze the trade-offs encountered during design; providing a way to deal with changes in requirements and design assumptions as well.

Future work

The nature and abstraction of the implemented function modelling-based tools can allow their adaptation to various industries and manufacturing technologies. Generalizability, in this sense, lies on the possibility of customizing the function tree representation with information about a product of interest. After all, function modelling techniques have been long proved to be versatile enough to be applied in, for instance, design of other aerospace components with traditional manufacturing technologies (Ballu et al., 2006; Raja and Isaksson, 2015) and even customizable AM medicine (Siiskonen et al., 2018); AM microreactors (Valjak et al., 2018) and software industry (Mylopoulos, et al., 1992; Bosch and Molin, 1999; Huang et al., 2007).

This thesis has been concerned with the introduction of a new manufacturing technology in space components. As technologies for space applications advance at a fast pace, future research needs to be performed to adapt the proposed design methodologies for supporting product design with technologies that are not only manufacturing related. Moreover, as product development is often concerned with the introduction of multiple technologies in the same product/product family, the impact of technology interactions in product design is of interest. At some point, the research activities will aim to answer questions such as:

- *How can the proposed product design support be adapted for introducing different technologies in space products?*
- *How can the interaction among different technologies be modelled in a product design support to facilitate their introduction in space products?*

The products redesigned in the research project RIQAM and Articles C and D are mostly mechanical. To extend the reach of the proposed design support, the design of other types of components, such as electrical components, must be included in the analysis. The interest in this analysis lays on the fact that the function modelling technique utilized (EF-M) was developed in the earlies 2000, when electromechanical components were not as usual as they are today. Furthermore, it is based on concepts that are even older, such as the way components interactions are classified (spatial, energy, information and material interactions) (Pimmler and Eppinger, 1994).

The research project CHEOPS enables the above-mentioned research interests as it provides a case study for the design of hall effect thrusters for satellite applications. This product is composed by mechanical, electromechanical and magnetic components. Due to the nature of this product, electro-magnetic interactions occur among certain components, providing a modelling challenge in terms of EM-F and components interactions classification (spatial, energy, information and material interactions). Moreover, the project is strongly influenced by the need for design considering several "*ilities*" such as adaptability, reliability, manufacturability, etc. These concepts are usually difficult to model and measure and are, therefore, difficult to consider in early design phases. Future research efforts will be concerned in their early modelling. For instance, this topic was touched upon in Article C, with the implementation of an adaptability (to future design requirements) function previously proposed by (Engel et al., 2017). However, as the terms of that function are mostly obtained through empirical studies, design efforts could be reduced if they could be modeled.

Research quality

Two criteria that ensure the quality of a scientific research is validity and reliability (Carmines and Zeller, 1979). Validity can be understood as the relationship between reality and research outcome (Did the researcher do the right things?). In the research activities presented in this thesis, several precautions were taken for ensuring research validity. Multiple product use-cases from different industrial companies were implemented and analyzed during empirical studies; moreover, different data sources were consulted for data validity. For instance, results from the literature review were challenged with observations and interviews data.

Through the research activities, several modelling strategies were used. For ensuring the validity of the achieved results, the steps taken to achieve those results were validated. For instance, the proposed DfAM methodologies are based on function models, and those models were validated through a process of "face validation" (Balci and Smith, 1986) which is the process where experts analyze the model and modify it accordingly. Other example is the fitness function implemented in Article C. For ensuring function validity, already validated (through extensive use) value functions were utilized for building the fitness function; then, a sensitivity analysis was performed to assess robustness and the results compatibility with reality.

Research reliability is related with the ability to repeat the implemented methods and arrive to the same results (Did the researcher do things right). To ensure reliability in this thesis, the data collection activities were planned and performed with detail, moreover the results of observations, literature studies and interviews were cross-checked with colleges and industrial practitioners from the empirical studies.

7

CONCLUSION

A conclusion about the results and their impact in future research activities

The space industry is transitioning into larger production volumes and reduced costs. This market shift impacts on the PD processes. Introducing AM in their portfolio, companies aim for design flexibility, cost and time to market reduction, and an increase in production volume while maintaining high product quality. However, several obstacles can hinder the introduction of AM in this industry. These obstacles can be generalized as lack of knowledge and experience, lack of technology development, and carried-over knowledge from traditional manufacturing technologies.

The lack of knowledge and technology development impair predictability and repeatability of the results, which render qualification activities expensive and problematic. Other consequence of the lack of experience in AM and the extensive experience about traditional manufacturing technologies (carried-over knowledge), is the design of AM component that are similar to their traditional predecessors.

This thesis proposes a DfAM design support based on function and constraint modelling. Besides supporting design practices, function models serve as a means for information storage, documenting the associations between functions, design solutions and design constraints. Moreover, the process of constraint classification and replacement can help acknowledging and removing the carried-over knowledge about traditional manufacturing technologies, which hinders AM design freedom.

The results in this thesis suggest that the abstract product representations provided by function modelling techniques are suitable for early design phases where product information is scarce. Moreover, these techniques support the introduction of new product functionalities and technologies as they facilitate design exploration and evaluation, understanding of the behavior of system elements, and validation. These benefits are achieved modelling the little information (about a design, new functionalities or new technologies) available at these early phases.

Models can also serve as a mean for recording and transmitting information and design decisions. Testing and validating system characteristics early, help the premature detection and correction of design errors, when the time and financial impact of design modifications are minimum (Holt et al., 2016; Borky and Bradley, 2019).

AM technologies enable great design opportunities but are often lacking a multidisciplinary view of the design requirements during early design phases. However, an early consideration of multidisciplinary requirements is problematic as information at these stages is scarce. To counteract the lack of information, models are implemented as they can facilitate design exploration and evaluation, using the little information available at these early phases.

The topic of this thesis is concerned with the introduction of a new manufacturing technology in space components requiring a design, or redesign effort. As technologies for space applications advance at a fast pace, future research needs to be performed to adapt the proposed design support to enable the introduction of technologies that are not manufacturing related. Moreover, as product development is often concerned with the introduction of multiple technologies in the same product/product family, the impact of technology interactions in product design is of interest.

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